



Combustion

Dan Bulzan, NASA Glenn Research Center
Fundamental Aeronautics 2007 Annual Meeting
New Orleans, LA
Oct 31, 2007

An overview of the emissions related research being conducted as part of the Fundamental Aeronautics Subsonics Fixed Wing Project is presented. The overview includes project metrics, milestones, and descriptions of major research areas. The overview also includes information on some of the emissions research being conducted under NASA Research Announcements.



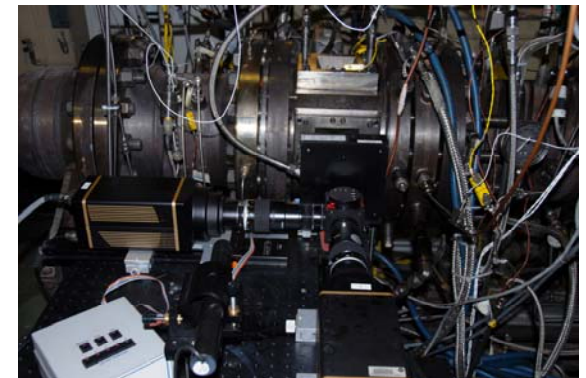
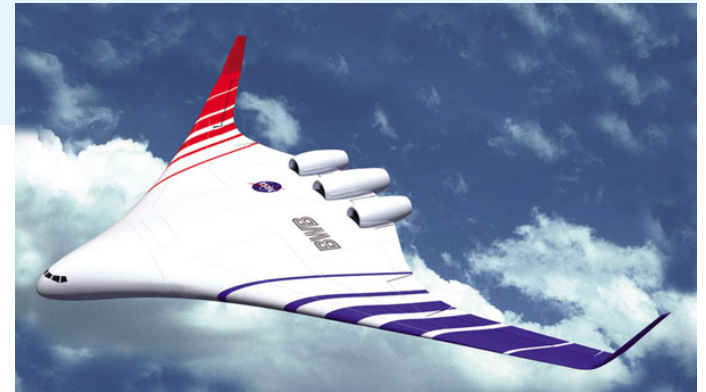
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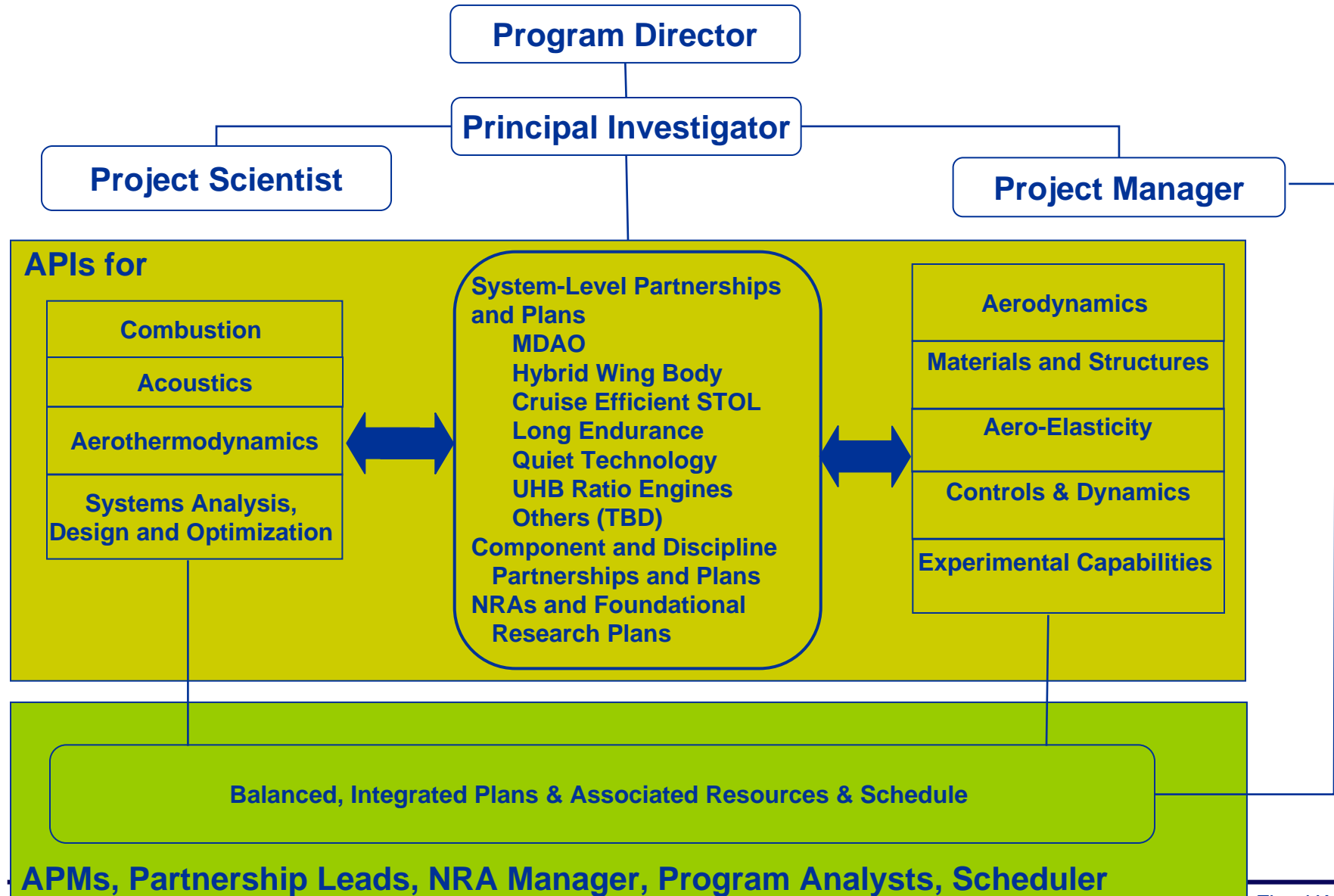
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Organization of SFW Project





System Level Metrics - Updated

.... technology for dramatically improving noise, emissions, & performance

CORNERS OF THE TRADE SPACE	N+1 Generation Conventional Tube w/Wing (2012-2015)	N+2 Generation Unconventional Hybrid Wing Body (2018-2020)
Noise (cum below Stage 3)	- 42 dB	- 52 dB
LTO NOx Emissions (below CAEP 2)	-70%	-80%
Performance: Aircraft Fuel Burn (relative to B737/CFM56)	-33%	-50%***
Performance: Field Length (relative to B737/CFM56)	-33%	-50%

N+1 Conventional



N+2 Hybrid Wing/Body



Approach

- Enable Major Changes in Engine Cycle/Airframe Configurations
- Reduce Uncertainty in Multi-Disciplinary Design and Analysis Tools and Processes
- Develop/Test/ Analyze Advanced Multi-Discipline Based Concepts and Technologies
- Conduct Discipline-based Foundational Research

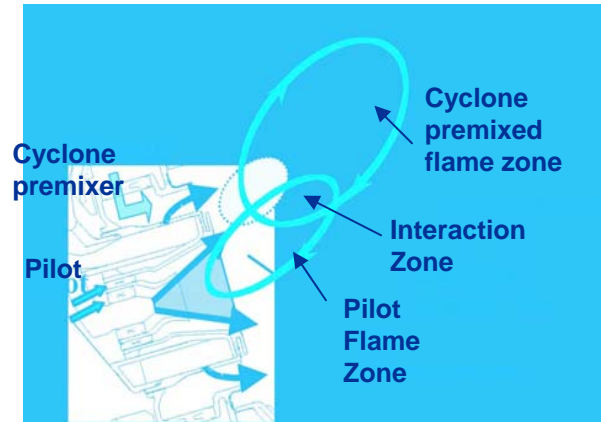
***Fuel burn for N+2 being validated



NOx Emissions Reduction

“N + 1” Conventional Small Twin

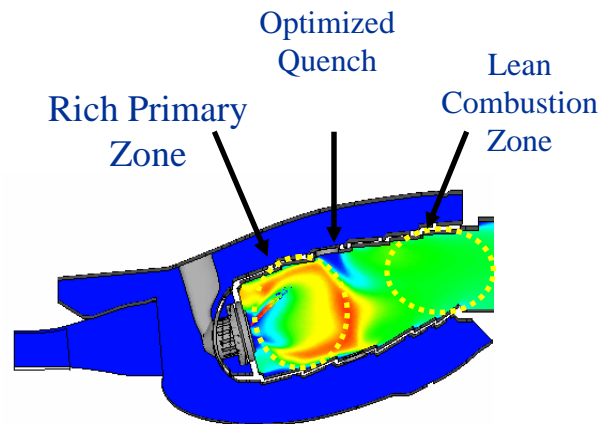
70% LTO NO_x reduction below CAEP/2
Target Next Generation Single Aisle (NGSA)
Annular combustor TAPS (GE)
Improved fuel/air mixers
TALON X (P&W)
Optimized quench section for improved mixing
Improved fuel/air mixing in rich zone



Cyclone Main with Pilot Concept

“N + 2” Hybrid Wing/Body

80% LTO NO_x reduction below CAEP/2
Improved CFD Modeling
Advanced combustor concepts
Advanced fuel/air mixers
Active combustion control
High temperature liners
Alternative fuels



Rich Burn Quick Quench Lean Burn Concept



Lean Direct Injection Multipoint Concept



Optimization - Performing Trades

Noise

Cum below Stage 3

Emissions

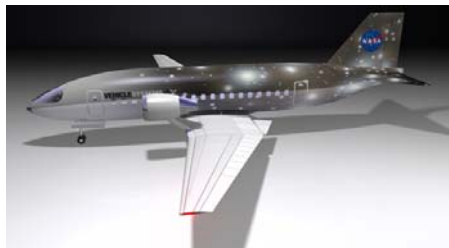
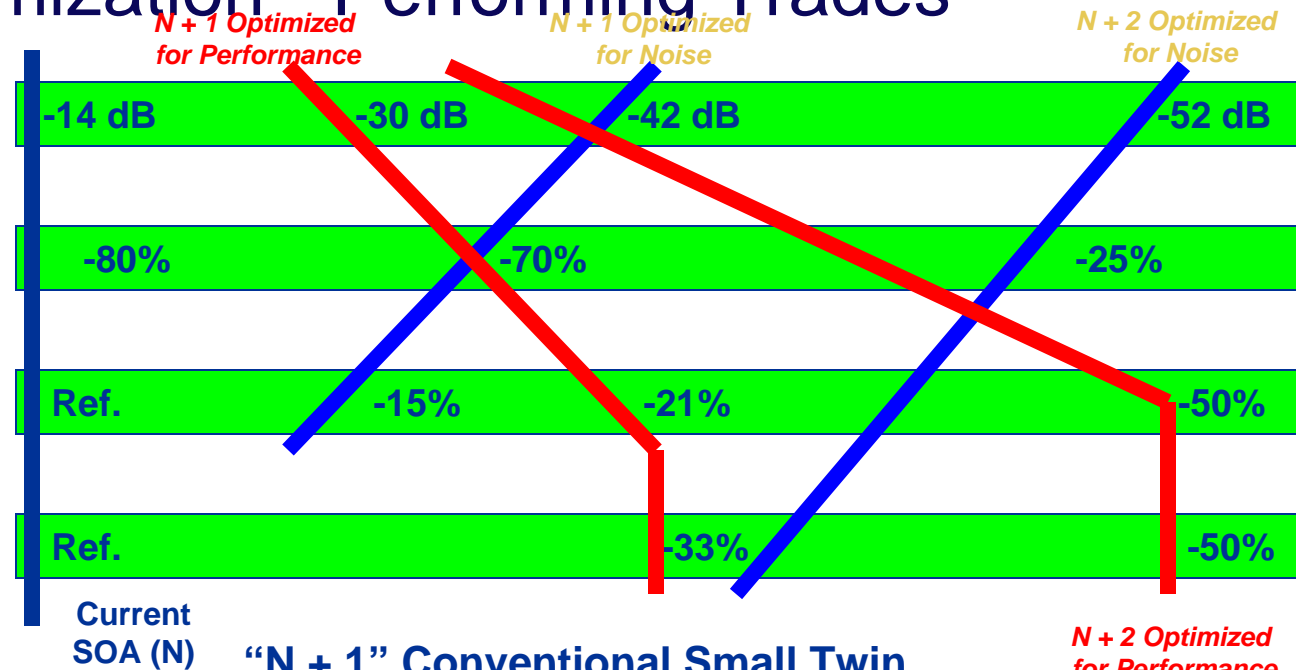
LTO NOx below CAEP/2

Performance

Aircraft Fuel Burn relative to 737/CFM56

Performance

Field Length relative to 737/CFM56



“N + 1” Conventional Small Twin

- Technologies available for 2012 – 2015 EIS (market permitting)
- Noise: UHB engines, reduced weight, low-noise fans & landing gear
- Emissions: advanced combustors (TAPS, TALONX, etc.)
- Performance: high power density engine cores, reduced weight, high lift

“N + 2” Hybrid Wing/Body

- Technologies available for 2018 – 2020 Initial Operational Capability
- Noise: shielding from above wing engines, low-noise airframe
- Emissions: alternative fuels, advanced combustion concepts
- Performance: embedded engines, morphing structures, low drag
- Field Length: cruise efficient STOL, high lift



Combustion Technical Approach

- NASA Research Announcement (NRA)
- Combustion Fundamental Research
 - Alternative Fuels
 - Fundamental Experiments
 - Physics-Based Model Development
- Combustion Technologies and Tool Development
 - Combustion CFD Code Development and Application
 - Low-emissions Combustion Concepts
- Multidisciplinary Analysis and Optimization



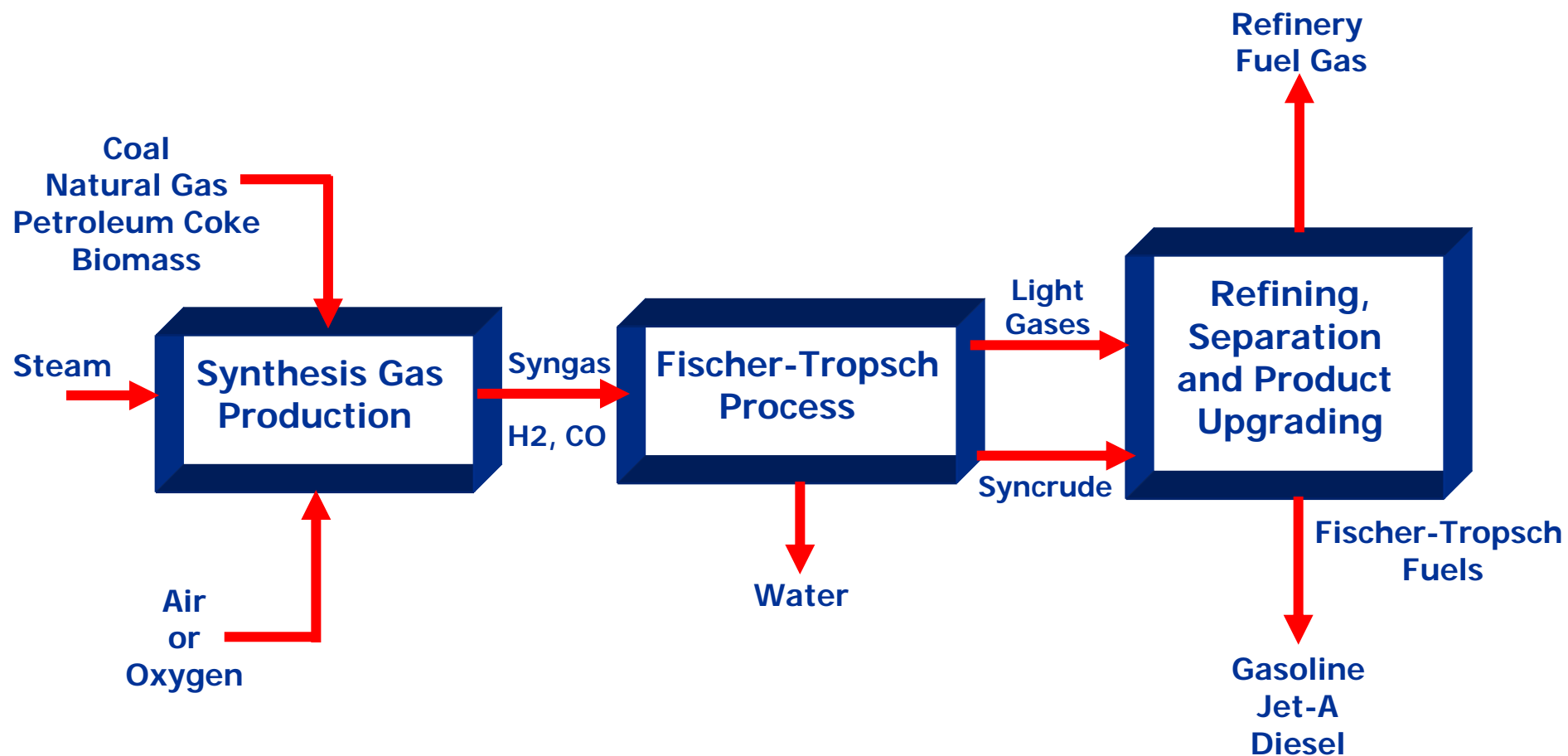
Alternative Fuels

- **Major Tasks**

- Buildup of Bldg 109 Alternative Fuels Laboratory
- Thermal Stability Measurements of alternative fuels
- Fundamental studies of Fischer-Tropsch Reaction kinetics
- Combustion Testing in laboratory scale burner, flametubes, and engines
- Database of alternative fuel thermochemical and physical properties
- Identification of suitable alternative fuels for use in aeronautics applications including biofuels
- Participate in planning/roadmap meetings with other agencies performing research on alternative fuels

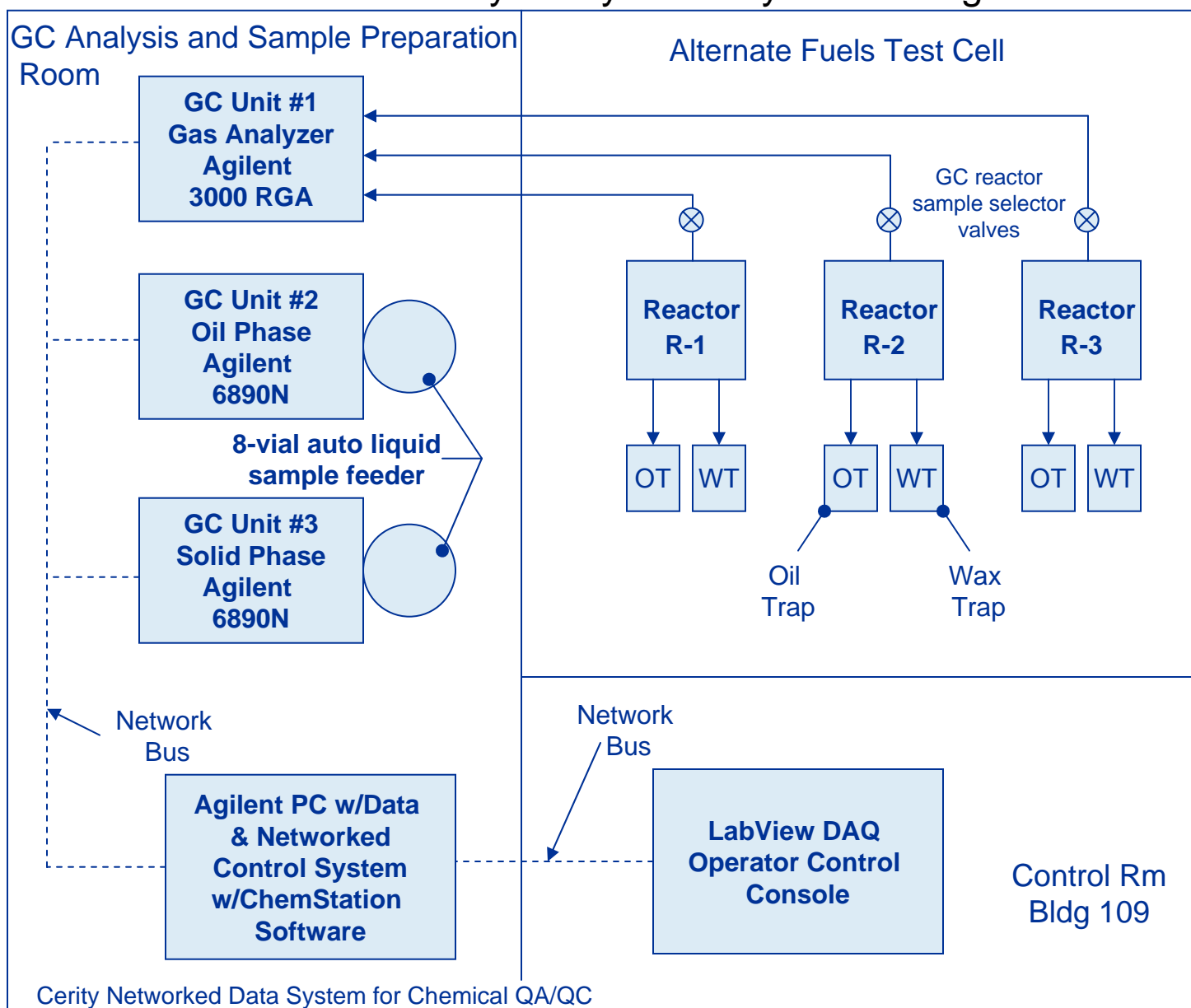
- **Status of Current Activities**

- Alternative Fuels Laboratory buildup on schedule, 12/30/07 completion
- Hot Liquid Process Simulator (HLPS) for thermal stability installed and initial testing is being conducted
- Currently installing alternative fuel system in NASA CE-5 combustion flametube facility, Nov,07 estimated completion
- Collaboration with AFRL for alternative fuel properties, combustion testing, and particulates measurements
- Purchased F-T fuel from Shell in conjunction with Air Force for combustor flametube and engine tests in FY08
- Simplified Technology Transfer Agreement with AR Associates to supply samples of biofuel for thermal stability analysis
- NRA funded studies for basic studies of F-T Reactor Kinetics (University of Kentucky)





GC Analyzer System Layout / Configuration.





Alternative Fuels



**F-T Reactors
installed in
Alternative Fuel
Laboratory**

**HLPS
Instrumentation**



- **Planned Activities**

- Testing in P&W 308 and UHB engines for Shell F-T fuel/Jet-A blends to measure gaseous and particulate emissions, November, 2007 – March, 2008
- Issue Request For Information (RFI) (Fall, 2007) for other alternative fuels suitable for aeronautics application including biofuels
- Purchase additional alternative fuel (may be combined with Air Force purchase for F-T fuel and also dependent on RFI responses)
- Alternative fuel testing using NASA DC-8 for static ground tests to measure gaseous and particulate emissions to allow complete disclosure of measurements
- Combustion flametube testing in NASA flametube facility of NASA 9-point LDI, Complex Multi-Swirler Mixer from GE, and other industry low emission combustion concepts
- Experiments to study algae, halophytes, jatropha, under fresh and saltwater conditions to measure production rates



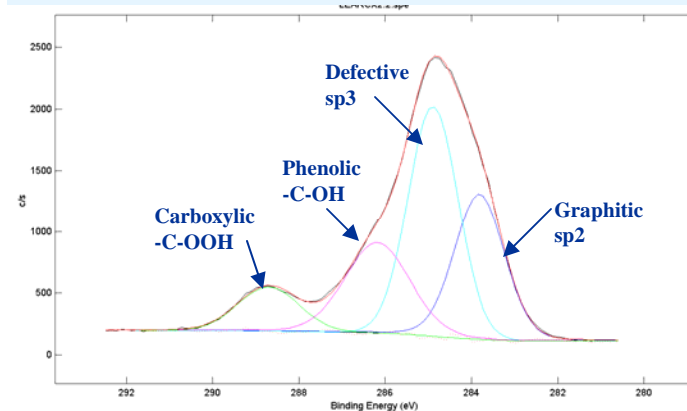
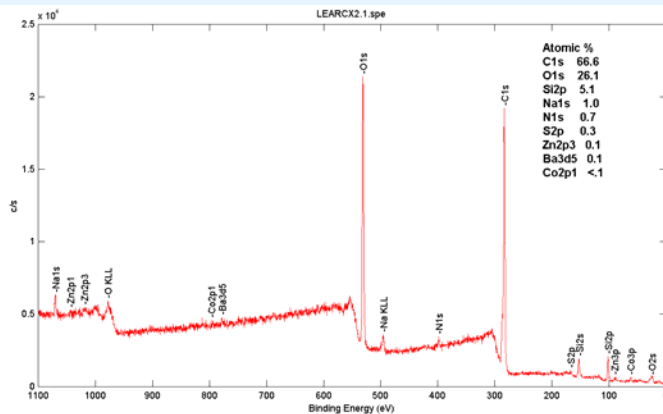
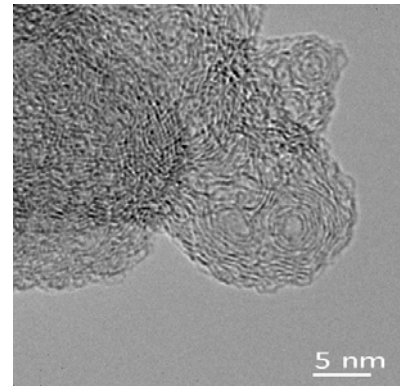
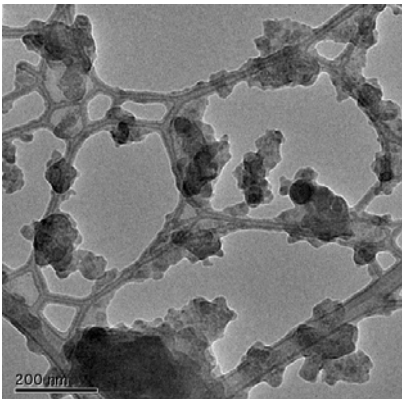
Fundamental Experiments

- **Fundamental experiments conducted in high-pressure laboratory scale SE-5 facility of increasing flow complexity using gaseous methane, gaseous heptane, liquid heptane, and multicomponent Jet-A and F-T fuel surrogates**
- **Design, fabrication, and buildup of low pressure flametube rig in CE-7 for fundamental experiments on single element LDI modules for low emissions combustor development**
- **Buildup of Flow Reactor in CE-24 for Chemical Kinetics mechanism development for Jet-A and Alternative fuel surrogates**
- **SiC fabrication and bonding research and MEMS fuel nozzle actuators for advanced LDI combustion concepts**
- **Particle Sampling and Probe Studies**
- **Exhaust plume particulate studies at sea level and subsonic cruise conditions in SE-11 Particle Altitude Simulation Laboratory**



Fundamental Experiments

- **NRAs**
 - **Effect of Particle Sampling Technique and Transport on Particle Penetration at the High Temperature and Pressure Conditions found in Gas Turbine Combustors and Engines, United Technologies Research Center**
 - **Electron Microscopy, Spectroscopy and Chemical Analysis of Aircraft Engine Particulate for Complete Physical and Chemical Characterization, Universities Space Research Association**
 - **Experimental Measurements of the Composition of Volatile Particles Present in Aircraft Gas Turbine Exhaust, Aerodyne Research**
 - **Model-Based Design of Improved High-Temperature, high-Pressure Particle Sampling Probes and Characterization of Chemical Composition of Volatile Particle Emissions, Aerodyne Research**

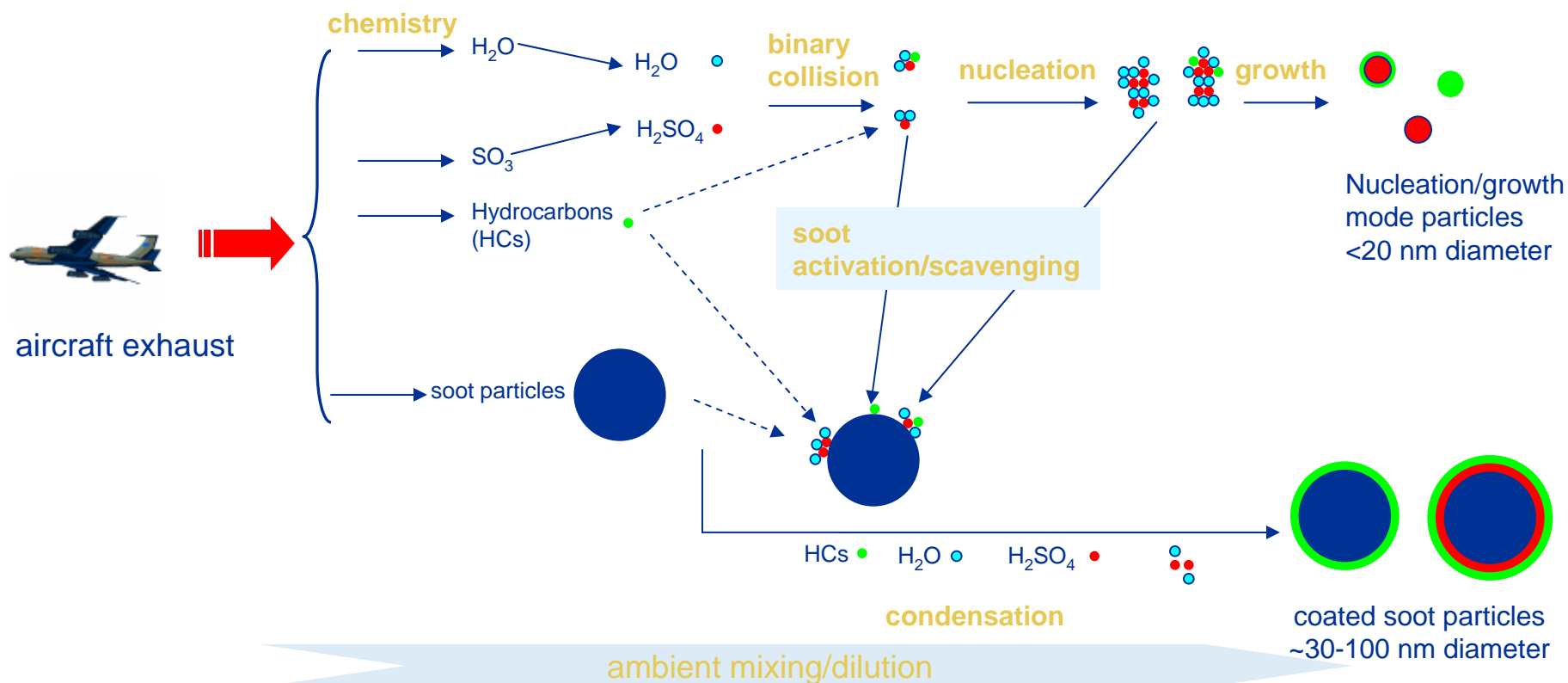




Experimental Measurements of the Composition of Volatile Particles Present in Aircraft Gas Turbine Engine Exhaust – Aerodyne Research, Inc.

M. T. Timko (PI), R. C. Miake-Lye (Co-I)

NASA GRC # NNC07CB57C



Motivation. The potential human health and environmental impacts of aviation pollution, especially particle emissions is poorly understood.

Background. Aircraft engines emit a mixture of soot and volatile gases. As pictured above, these gases cool to ambient temperature by mixing with ambient air and convert to the particle phase by condensation and nucleation/growth. The nucleation/growth mode particles and soot coatings are complex mixtures of sulfuric acid, water, partially burned hydrocarbons, and engine oil.

Objective. This work aims to characterize the composition of aviation particles and their evolution during atmospheric processing and dilution.

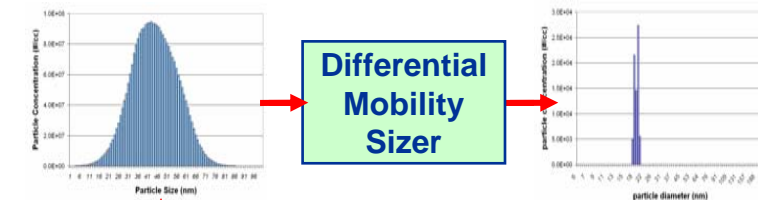
Effect of Particle Sampling Technique & Transport on Particle Penetration at the High Temperature & Pressure Conditions found in Gas Turbine Combustors & Engines- UTRC

Year 1 Objective:

Develop techniques to quickly & accurately evaluate sampling line size-dependent transmission losses

Approach:

Use laboratory measurements to develop and evaluate low-order modeling



Sample Line Variables:

- Tubing diameter, length, type
- Sample flowrate
- Bends
- Ageing

Up

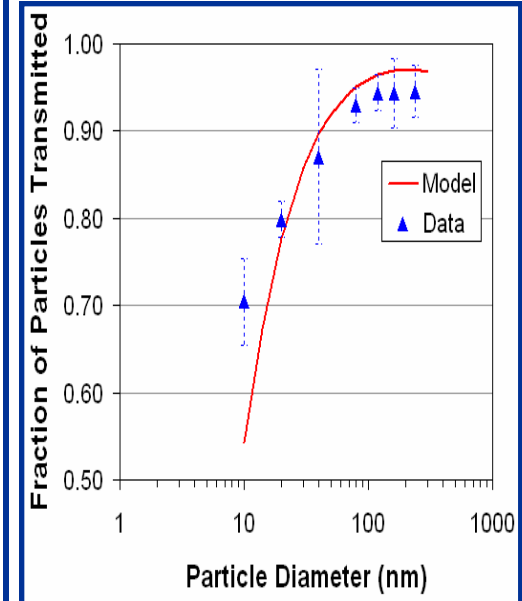
Condensation
Particle
Counter

Down

Condensation
Particle
Counter

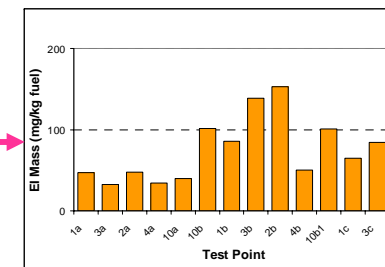
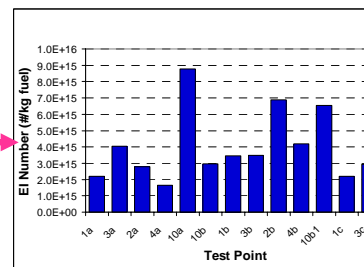
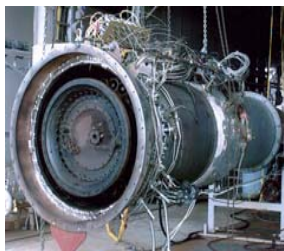
Expected outcome:

Use model to correct engine/combustor emission data for line losses



Year 2 Objective:

Acquire particulate measurements in high pressure and high temperature combustion experiments

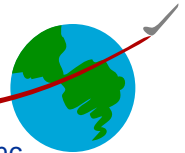




Model-Based Design of High-Temperature, High-Pressure Particle Sampling Systems and Characterization of Chemical Composition of Volatile Particles

Aerodyne Research, Inc.

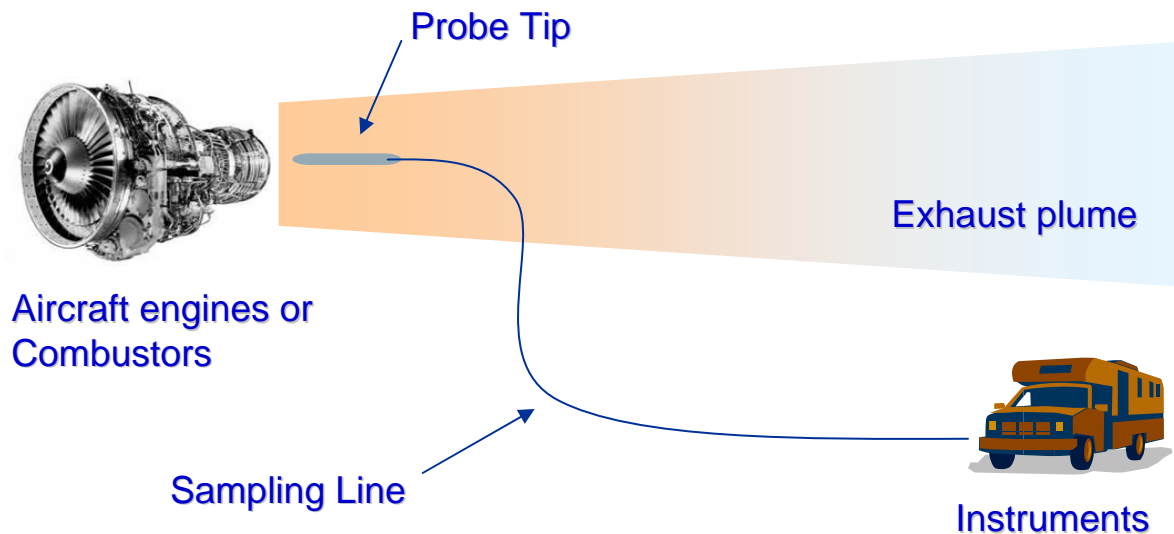
Hsi-Wu Wong (PI), Richard C. Miake-Lye (Co-I), NASA Contract No. NNC-07-CB58C



Aerodyne Research, Inc.

Objectives

- 1) Computer-guided design of particle sampling system (probe tip and sampling line) under high-temperature, high-pressure environments
- 2) Model elucidation of microphysics of formation of volatile aviation particles in the plume and sampling systems



Motivations

- 1) Aircraft-emitted particles have gained increased attention due to their potential impacts on regional air quality, health, and climate
- 2) Gas turbine combustor studies allows one to determine optimized emission performance at an early design stage, but feasibility of applying current sampling systems to these environments is uncertain
- 3) Chemical composition and particle size distribution of aircraft-emitted particles are sensitive to sampling system design, engine operating parameters, and atmospheric conditions, and repeatable and accurate measurements are challenging



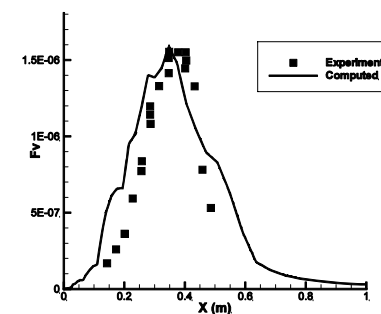
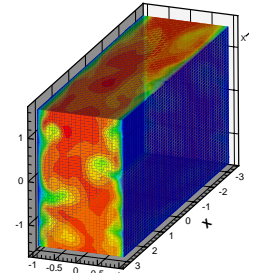
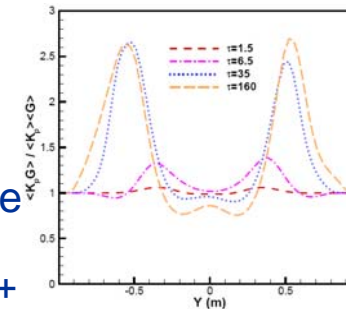
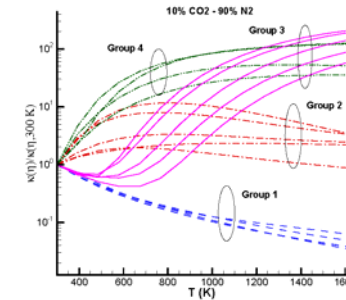
Improved Physics-Based Model Development

- **Implementation of Radiation Heat Transfer Models into NCC**
- **NRAs**
 - **Subgrid Combustion Models for the Next Generation National Combustion Code, Georgia Institute of Technology**
 - **Integrated Large Eddy Simulation of Multi-Phase Turbulent Reacting Flows for Realistic Gas-Turbine Combustors, Stanford University**
 - **LES Modeling of Spectral Multiphase Radiation and Turbulence/Chemistry/Radiation Interactions in Reacting Turbulent Flow, The Pennsylvania State University**
 - **Comprehensive Chemical Kinetics of Conventional and Alternative Jet Fuels for Aeropropulsion Combustion Modeling, Case Western Reserve University**
 - **Experimental and Modeling Studies of the Combustion Characteristics of Conventional and Alternative Jet Fuels, Reaction Design**



LES Modeling of Spectral Multiphase Radiation and Turbulence/ Chemistry/Radiation Interactions in Reacting Turbulent Flow

- Spectral Radiation Modeling
 - Hybrid multiscale/multigroup FSK method
 - On-the-fly construction of k-distributions
 - Gas-phase mixtures + soot + hot walls
- LES in Canonical Configurations
 - Nonreacting and reacting planar channel flows
 - Systematic variations in optical thickness
 - Isolation of TRI contributions
- PDF-Based Modeling of Laboratory-Scale Nonpremixed Jet Flames
 - Detailed gas-phase thermochemistry + detailed soot models + method-of-moments
 - Thermochemistry validation in laminar flames
 - Comparisons with experimental data



NASA Grant # NNX07AB40A

Michael Modest (PI) and Daniel Haworth (coPI)

PENNSTATE





Comprehensive Chemical Kinetics of Conventional and Alternative Jet Fuels for Aeropropulsion Combustion Modeling

PI: Chih-Jen Sung

Case Western Reserve University, Cleveland, Ohio

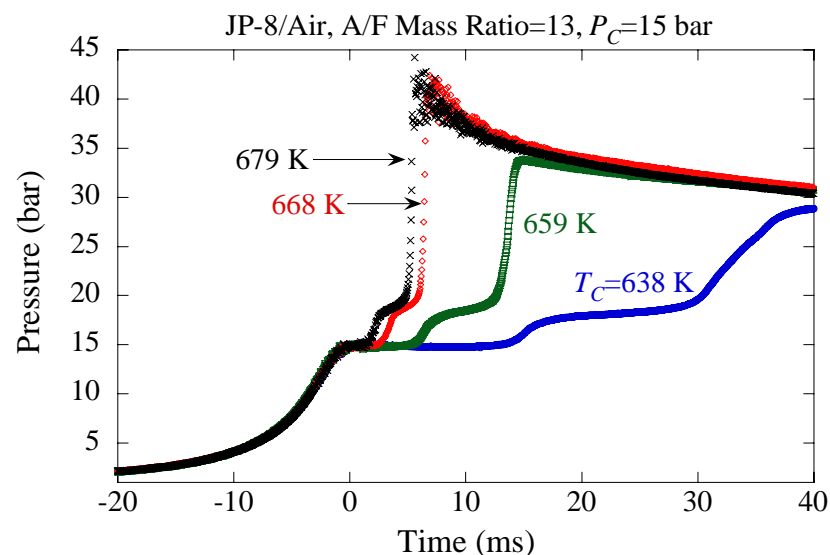
Objective: Development of comprehensive detailed and reduced kinetic mechanisms of jet fuels for chemically-reacting flow modeling.

Scientific Challenges:

- Developing experimental facilities capable of handling higher hydrocarbons and providing benchmark combustion data.
- Determining and understanding ignition and combustion characteristics, such as laminar flame speeds, extinction stretch rates, and autoignition delays, of jet fuels and hydrocarbons relevant to jet surrogates.
- Developing comprehensive kinetic models for jet fuels.

Major Accomplishments – Year 1:

- Developed and characterized experimental facilities for handling high-boiling-point liquid hydrocarbons and real jet fuels.
- Obtained extensive experimental data and assessed model performances for *n*-decane autoignition.
- Obtained experimental data for ignition delays of JP-8, Sasol fuel, and blends of toluene+isooctane and toluene+diisobutylene-1.
- Developed tools for automatic and efficient minimization of detailed kinetic mechanisms.
- Conducted computational fluid dynamics simulation of a rapid compression machine with detailed and reduced chemistry.



Relevance to NASA: Experimental data obtained will be used for development of comprehensive, computationally efficient kinetic models suitable for developing energy efficient aero-combustors with reduced emissions.

Grant #: NNX07AB36A

Program Monitor: Dr. Krishna P. Kundu

PI Contact information: Dr. Chih-Jen Sung
Email: cjs15@case.edu, Ph. #: 216-368-2942



Reaction Design and USC are developing validated mechanisms for alternative fuels

- Award # NNC07CB45C-Y1-Q1, 05-2007 through 04-2009
- Experimental and Modeling Studies of the Combustion Characteristics of Conventional and Alternative Jet Fuels
- PI: Ellen Meeks
- Co-Investigators:
 - Reaction Design: K. Puduppakkam, C. Naik, C. Wang, A. Modak
 - Dr. Charlie Westbrook (consultant to Reaction Design)
 - Univ. Southern California: Profs. F. Egolfopoulos and T. Tsotsis
- Objectives:
 - Obtain comprehensive set of fundamental data on combustion behavior of alternative (bio & F-T) jet fuels and associated model (surrogate) fuels
 - Flame experiments
 - Validated and reduced chemistry models
 - Identify differentiating characteristics of molecular fuel components that can be used in the design of optimal fuel-processing



Combustion CFD Code Development and Application

- **NCC assessment using v 1.1.8 for non-reacting and reacting single element LDI data at atmospheric pressure**
- **Gen 1 atomization and secondary liquid breakup model incorporated into NCC**
- **Very Large Eddy/Partially Resolved Navier-Stokes module integration into NCC**
- **NCC efficiency improvements for massively parallel processing**
- **Reacting flow calculations using data from SE-5 fundamental experiments and CE-5 flametube experiments**
- **Implementation of improved NRA models into NCC**
- **LES code implementation from NRA research activities**

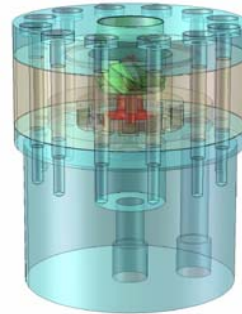
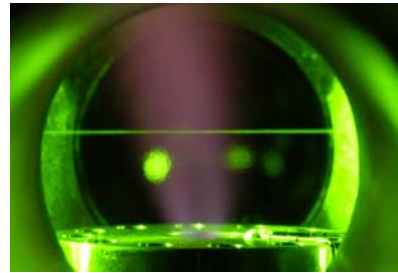
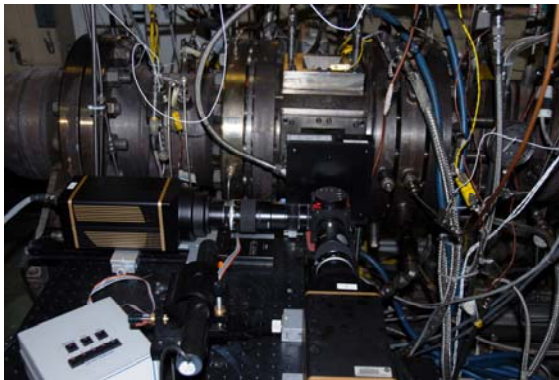


Low-Emissions Combustion

- **Design and installation of second fuel system in CE-5 for on-line blending of alternative fuels**
- **Code validation experiments for NASA 9-point LDI combustor concept**
- **Gaseous and particulate emissions measurements for NASA 9-point LDI with Fischer-Tropsch fuel**
- **Code validation experiments for GE Complex Multi-Swirler Mixer configurations**
- **Gaseous and particulate emissions measurements for GE Complex Multi-Swirler Mixer configuration with Fischer-Tropsch fuel**



NASA Facilities



CE-5 High Pressure
Flametube Stand 2



SE-5 High-Pressure
Laboratory Scale
Burner



SE-11 Particle
Altitude Simulation
Laboratory



Multidisciplinary Analysis and Optimization

- **Provide gaseous and particulate correlations for use in MDAO codes**
- **Provide support for higher fidelity emissions models being developed under NRA**
 - **Enhanced Modeling and Analysis for Emission Prediction, Georgia Institute of Technology**

Higher Fidelity Emissions Model Requirements

- More physics based
- Not just a function of temperature and pressure
- Efficient and fast – Not a CFD model
- Parametric
- Capable of on and off-design analysis
- Generic enough to be able to model new combustor designs
- Integrated with NPSS to bring improved emissions prediction to the engine system level



Enhanced Emissions Prediction Project

- The URETI project successfully demonstrated the approach for a single combustor
 - Developed Geometry Model
 - Evaluated Geometry Model based on E³ Combustor Data
 - Evaluated combustor emission based on E³ Combustor Results
 - Embedded Geometry model to NPSS
- For a useful design tool, the URETI results must be extended to the general case
- Technical challenges
 - Complexity of design space
 - Lack of solid guideline about how to define Network of Reactors' Structure
 - Non-Linearity of combustion processes
 - Metamodel creation
 - CO and UHC (Specifically for Off-Design)



Approach & Project Plan

- Lessons learned in URETI project can be extended to the more general case
 - The combustor may be decomposed into functional elements
 - Both geometry and combustion models
 - The geometry model is based on pre-defined combustion elements related to combustion zones
 - The combustion model is a 2-D, CFD-based chemical reaction network model
 - The geometry model and the combustion model will be coupled together based on characteristics of the combustion zones
- Project plan is divided into three phases:
 - Phase 1: Mature & integrate geometry model
 - Phase 2: Mature & integrate combustion model
 - Phase 3: Mature & integrate coupled combustor model



Session Agenda

- **Combustion Overview, *Dr. Dan Bulzan, NASA GRC***
- **Assessment of the National Combustion Code, *Dr. Nan-Suey Liu, NASA GRC***
- **Integrated Multi-Phase and Combustion Modeling for Large-Eddy Simulation of Realistic Gas-Turbine Combustors, *Dr. Heinz Pitsch, Stanford University***
- **Large Eddy Simulation of Spray Combustion in Swirling Flows, *Dr. Suresh Menon, Georgia Institute of Technology***
- **NASA 9-Point LDI Code Validation Experiment, *Dr. Yolanda Hicks, NASA GRC***
- **Development of Standard Practices for Characterizing Gas-Turbine Engine Particle Emissions, *Dr. Bruce Anderson, NASA LaRC***